

4. ATMOSPHERICS MODELING

4.1 INTRODUCTION

EPA has conducted a risk screen of possible alternatives to ozone depleting substances (ODSs) as part of its implementation of Section 612 of the Clean Air Act Amendments of 1990. Class I substances include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, and methyl chloroform. Atmospheric changes from the use of Class I ODSs have potentially serious consequences for human health and the environment. Depletion of stratospheric ozone increases the amount of biologically active ultraviolet radiation (UV-B) at the earth's surface. Among the consequences of increased UV-B are the increased incidence of cataracts and skin cancers, damage to plants and animals, and damage to polymers (chemical compounds often used in plastics, paints, and coatings).

This chapter presents estimates of the potential atmospheric and human health effects of alternatives to ODSs in the aerosols sector. The remainder of this chapter is divided into the four following sections: Section 4.2 briefly reviews the aerosol end uses and substitutes; Section 4.3 describes the baseline for the analysis; Section 4.4 details the modeling framework used to quantify the atmospheric and human health effects of the alternatives; Section 4.5 presents the results of the analysis; and Section 4.6 presents a qualitative discussion of global warming and global warming potentials.

4.2 AEROSOL END USES AND SUBSTITUTES

As discussed in Chapter 2, ODSs used in the aerosols sector have been grouped into propellant and solvent end use applications. Substances used primarily as propellants are CFC-12, CFC-114, HCFC-22, and HCFC-142b, and substances used as solvents are CFC-11, CFC-113, methyl chloroform (MCF), and HCFC-141b.

This chapter examines potential atmospheric effects associated with alternatives that may replace HCFC-22 in propellant applications, and CFC-11, CFC-113, MCF in solvent applications. The analysis does not assess the impacts of potential substitutes for HCFC-141b and HCFC-142b because of their limited use. Also, this analysis does not consider impacts of substitutes for CFC-12 and CFC-114 used as propellants in medical applications, as the substitutes for these applications are in the developmental stage. In addition, substitutes in medical applications will have to undergo FDA approval, potentially a three- to five-year process.

The primary substitutes for propellant uses of HCFC-22 are hydrocarbons; hydrofluorocarbons (HFCs); HFCs blended with dimethyl ethyl (DME); compressed gases; and not-in-kind systems. Under the Class II ban, the use of HCFCs in aerosol products will not be allowed after January 1, 1994, except for certain product categories exempted by EPA. To account for exempted product categories, it was assumed for the purposes of this analysis that propellant substitutes for HCFC-22 will replace only 50 percent of its current use.

The primary substitutes for the solvent/diluent uses of CFC-11, CFC-113, and MCF are petroleum distillates; oxygen-containing hydrocarbons; HCFC-141b; terpenes; chlorinated solvents; and water-based formulations. Because EPA has exempted certain uses of CFC-11 and CFC-113 in aerosol solvent applications under the Class I ban, it is assumed that some use of CFCs in aerosols will continue. For this analysis, it was assumed that 50 percent of the exempted CFC-11 and CFC-113 use will continue and that the substitutes will apply to only the remaining 50 percent of the usage.

4.3 THE BASELINE FOR THE ANALYSIS

The baseline provides a benchmark against which the effects of possible substitution scenarios can be measured. An appropriate baseline incorporates assumptions regarding chemical emissions in the particular end use being examined, but at the same time it must account for all other sources of emissions of relevant compounds both in the U.S. and in the rest of the world (ROW). A global baseline is required because the incremental atmospheric effects of emissions in an end use depend on the quantity emitted from all other end uses worldwide (including end uses in other sectors, such as refrigeration, sterilization, etc.).

The baseline is described in three steps. First, the uniform assumptions made throughout the analysis are specified. Second, the assumptions that are applied to all of the end uses other than the one in which multiple substitutes are being compared are specified. Finally, the baseline assumptions used within an end use when evaluating multiple substitutes are specified.

4.3.1 Uniform Assumptions Made Throughout the Analysis

This section describes the uniform phaseout and recycling assumptions made throughout the analysis. The U.S. phaseout assumptions are listed in Exhibit 4-1. The exhibit lists the last year in which a given chemical can be produced for use in either new equipment or existing equipment. Other developed countries (Canada, Japan, Australia, New Zealand, and the nations of Western Europe) are assumed to follow the same schedule. The phaseout of ODSs in developing countries is assumed to lag that of the developed world by a decade. In addition, this analysis assumes that CFCs and HCFCs are recycled beginning in 1992 during the servicing and disposal of certain refrigeration equipment and that HFCs are likewise recycled starting in 1995. These recycling options are implemented in both the U.S. and the rest of the world (with a ten-year lag for developing countries).

EXHIBIT 4-1
PHASEOUT ASSUMPTIONS FOR THE UNITED STATES

Chemical Compound	Phaseout Date for New Equipment	Phaseout Date for Existing Equipment
CFCs, methyl chloroform and carbon tetrachloride	1996	1996
halons	1994	1994
methyl bromide	2001	2001
HCFC-141b	2003	2003
HCFC-22 and HCFC-142b	2010	2020
All other HCFCs	2015	2030

4.3.2 Assumptions Made for All Other End Uses

This section summarizes the substances industry is assumed to choose to replace CFCs, halons and MCF in all end uses other than the one in which multiple substitutes are being compared. Although in a few sectors it remains uncertain which substitutes will be chosen, a "best estimate" substitute or combination of substitutes was assumed for each end use under the 1996 phaseout in order to best approximate total worldwide emissions of Class I and Class II substitutes. These substitution scenarios were developed based on EPA's best judgment of the likely substitutes to be used in each end use under the 1996 phaseout.

4.3.3 Assumptions Made Within the End Use of Concern

This section describes the baseline assumptions used within the end use in which multiple substitutes are to be compared (e.g., propellant applications in aerosol products). In this analysis two different baselines are used to present the results of the substitution scenarios. Before detailing these baselines, it is important to note that the choice of the baseline affects the presentation, and not the substance, of the results. Under either of the baselines described below, the relative differences between the substitutes with respect to ozone depletion will be the same. The absolute results presented for each substitute will, however, differ between the two baselines.

Each of the baselines used with the end use of concern are discussed below. One is a "no-risk" baseline; the other is a "no-substitution" baseline. These two baselines bound the range of health effects, since the first examines impacts from a risk-free scenario and the second presents effects assuming continued use of all ODSs.

4.3.3.1 Ideal Substitute Baseline

The "ideal" substitute is a hypothetical alternative that has an ozone depletion potential (ODP) of zero. The concept of the "ideal" substitute was developed to provide a "no-risk" point of reference from which actual alternatives could be compared against one another.

In this case, the difference between substitute and baseline scenarios isolates the effects of implementing the substitute in the U.S. relative to an ideal or "no-risk" substitute. As presented schematically in Exhibit 4-2, the reported effects of a substitute are the difference between the estimated effects of the substitution scenario and the "ideal" substitute baseline. The "ideal" substitute baseline consists of the "ideal" substitute in the end use of concern in the U.S. only and the "best estimate" substitute in all other end uses – both in the U.S. and in the rest of the world. The substitution scenario consists of the substitute in the end use of concern in the U.S., and the "best estimate" scenario in all other end uses.

The advantage of the "ideal" substitute baseline is that it allows for a "no-risk" point of reference for presentation purposes but accounts for changes in atmospheric conditions caused by activity in other end uses. It must be emphasized that the "ideal" substitute is only used as a reference point. In all end uses, the relevant comparisons are those between one substitute and another, not between the substitute and the ideal.

The model includes consideration of speed of market penetration. In all analyses, the "ideal" substitute fully penetrates the market in 1992. Alternatives in the "best estimate" scenario can enter the market at different dates and penetrate at different rates. None, however, begin penetrating before the "ideal" substitute. As a result, a substitute that has low ODP but only penetrates that market slowly

shows adverse health effects that are an artifact of the modeling, since until the time the substitute becomes available, ODSs must continue to be used.

EXHIBIT 4-2
SUMMARY OF SCENARIOS USED IN ATMOSPHERICS RUNS
TO CALCULATE IMPACTS RELATIVE TO "IDEAL" BASELINE

	United States		Rest-of-World	
	End Use of Concern	All Other End Uses	End Use of Concern	All Other End Uses
BASELINE SCENARIO	"Ideal" Substitute	Best Estimate Substitute	Best Estimate Substitute	Best Estimate Substitute
SUBSTITUTION SCENARIO	Substitute	Best Estimate Substitute	Best Estimate Substitute	Best Estimate Substitute

4.3.3.2 No-Substitution Baseline

Under this baseline, the incremental performance of each substitute within an end use is judged against a no-substitution baseline (i.e., continued use of Class I substances within the end use). This option clearly indicates the reduction in ozone depletion risk associated with replacing the use of Class I compounds with each of the potential substitutes and allows for direct comparisons of the risk reduction achievable through each substitute.

In this case, the difference between substitute and baseline scenarios isolates the effects of implementing the substitute in the U.S. relative to a scenario that assumes the continued use of the Class I compound. As presented schematically in Exhibit 4-3, the reported effects of a substitute under this baseline are the difference between the estimated effects of the substitution scenario and the no-substitution baseline. The no-substitution baseline consists of the continued use of the Class I compound in the end use of concern in the U.S. only and the "best estimate" substitute in all other end uses – both in the U.S. and in the rest of the world. The substitution scenario consists of the substitute in the end use of concern in the U.S., and the "best estimate" scenario in all other end uses.

The intent of the Agency in presenting the resulting of the tradeoff analysis relative to the no-substitution baseline is to indicate that all of the substitutes analyzed are substantially less harmful to the ozone layer than continued use of CFCs. In presenting the results in this fashion, however, EPA is cognizant of the fact that the reduction in ozone depletion risks due to the phaseout of Class I compounds are attributable to the Class I Phaseout Rule and not the Safe Alternatives Program.

EXHIBIT 4-3
SUMMARY OF SCENARIOS USED IN ATMOSPHERICS RUNS
TO CALCULATE IMPACTS RELATIVE TO "NO SUBSTITUTION" BASELINE

	United States			Rest-of-World	
	End Use of Concern	All Other End Uses		End Use of Concern	All Other End Uses
BASELINE SCENARIO	Continued CFC Use	Best Estimate Substitute		Best Estimate Substitute	Best Estimate Substitute
SUBSTITUTION SCENARIO	Substitute	Best Estimate Substitute		Best Estimate Substitute	Best Estimate Substitute

4.4 OVERVIEW OF THE MODELING APPROACH

This section provides a brief description of the Atmospheric and Health Effects Framework (AHEF), the modeling framework used to assess the global environmental impacts of alternatives to Class I substances in the United States.

4.4.1 Chemical Use

The starting point of an AHEF analysis is to forecast the consumption of the relevant chemical compounds in each of the end uses in each sector. For U.S. estimates, this task is usually performed by the Vintaging Model, which simulates the chemical requirements of the various equipment types in each end use over their lifetimes. The Vintaging Model has been used to support several significant Agency rulemakings, including the phaseout of Class I and Class II compounds under Section 604 of the Clean Air Act. It is documented in Appendix A of EPA's *Regulatory Impact Analysis: Compliance with Section 604 of the Clean Air Act for the Phaseout of Ozone Depleting Substances* (EPA 1992), which was included in the Phaseout rulemaking docket and was subject to public review and comment.

For other regions of the world, chemical use estimates are typically derived by applying the London Amendment reduction schedule to estimates of what demand would be in the rest of the world had this phaseout never occurred.

4.4.2 Chemical Emissions

Emissions of a compound into the atmosphere are not necessarily simultaneous with use. The delay between use and emission of a compound depends on the kind of equipment in which the compound is employed. For example, hermetically sealed refrigerators emit CFCs over a very long period of time, whereas packaging foams emit similar compounds in less than one year. AHEF simulates compound emissions by means of release functions which specify the time delay between use and emissions for each particular end use.

4.4.3 Atmospheric Effects

The output from the emissions module are used in an atmospheric model, the Atmospheric Stabilization Framework (ASF), that predicts changes in stratospheric ozone associated with changes in

atmospheric composition. ASF computes the globally and annually averaged concentrations of climatically important atmospheric constituents, taking into account various feedbacks between climate parameters and the constituents themselves. Examples of feedbacks accounted for in ASF are:

- The dependence of a compound's atmospheric lifetime on column ozone and temperature;
- Radiative and chemical feedbacks due to water vapor;
- Ocean absorption;
- Atmospheric circulation effects; and
- Chemical interactions between compounds.

ASF relies on simple empirical relations based either on observations or on the results of more complex models in order to quantify physical feedbacks. In particular, the dependence of model ozone on stratospheric chlorine is adjusted so that it predicts a historical ozone depletion equal to that observed for the current atmosphere. In addition, ASF input parameters are adjusted to give column ozone changes that are consistent with consensus ODP estimates.

The ASF is a "consensus" model developed by a committee of prominent atmospheric scientists in government, academia, and private consulting firms. It was designed to approximate the behavior of more sophisticated two and three-dimensional physical models without requiring the computing power needed for physical simulations. Additional information on the ASF can be found in National Aeronautics and Space Administration Conference Publication 3023, *An Assessment Model for Atmospheric Composition* (NASA 1989).

4.4.4 Human Health Effects

The ozone column changes predicted by the ASF are inputs to a health effects model that estimates the number of skin cancer cases and fatalities that result from the scenario modeled. Estimates of skin cancers include both melanoma and non-melanoma cancers and represent all cases experienced by individuals born in the United States before 2030.

In order to quantify the human health impacts of ozone depletion in the U.S., the globally averaged ozone depletion predicted by ASF is converted to estimates of depletion by latitude. This latitudinal variation is estimated using simple regression techniques from a prior two-dimensional modeling study (Isaksen, 1986). Results from a separate UV model are in turn used to estimate changes in UV-B intensity associated with the latitudinally-varying ozone depletion.

Human health effects are computed by AHEF as a function of UV-B exposure. The effective exposure of various population cohorts, representing different sexes and age groups, is estimated using appropriate factors that weight exposure at various stages during a person's lifetime. Empirical "dose-response" relationships for each cohort are then used to predict changes in skin cancer and cataract incidence over time.

The human health effects model was reviewed in 1987 as part of an EPA Science Advisory Board review of *Assessing the Risks of Trace Gases that Can Modify the Stratosphere* (EPA 1987).

4.5 MODEL RESULTS

This section presents the results of the atmospheric screening analysis and lists several considerations that are helpful to interpreting them.

4.5.1 Description of Results

The results of running the ASF model are presented in Exhibits 4-4 through 4-7. For each ODS currently used in aerosol applications, there are four parts to each exhibit (e.g., the atmospheric effects of substituting for HCFC-22 can be found in Exhibits 4-4-A through 4-4-D). Parts A and B of each exhibit present the atmospheric results for substitutes compared to the "ideal" baseline. Parts C and D of each exhibit present results relative to the "no-substitution" baseline. Each exhibit contains a two tables and a two graphs. The tables list the assumptions regarding the availability and replacement potential of each alternative and estimated atmospheric and health effects resulting from those assumptions. Note that numbers in parentheses represent decreases from the baseline. The graphs illustrate the change in cumulative Cl_x in 2075 for each of the alternatives.

More specifically, the following information is provided:

Start Date: The year in which the alternative option is expected to be commercially available (i.e., after all research and development is complete). A start date of 1992 indicates that the alternative is currently available.

Years to Maximum Market Penetration: The number of years it would take for an alternative, once it became commercially available, to reach its maximum possible use in the end use market.

Maximum Market Penetration: The maximum, technically feasible percentage of total ODS consumption in an end use that can be replaced by the alternative.

Cumulative Cl_x : This is a measure of a change in the total quantity of chlorine in the stratosphere over time. More technically, it is the integral of the Cl_x curve above two parts per billion.

Skin Cancer Cases: The estimated change in the number of cases of melanoma and non-melanoma skin cancers experienced by individuals in the U.S. population born before 2030. The estimate of skin cancers includes fatalities that may result from these cancers.

Skin Cancer Fatalities: The estimated change in the number of fatalities due to melanoma and non-melanoma skin cancers of individuals in the U.S. population born before 2030. Skin cancer fatalities are a small portion of the total number of skin cancer cases.

4.5.2 Interpreting the Results

When interpreting the results, one should be aware of the following:

- Even an ozone-safe alternative can have skin cancers attributed to it if it penetrates the end use market after the "ideal" substitute. This is because the results presented for each alternative account for both the effects of that alternative and the effects of the CFC use that occurs in the period before the implementation of the alternative and after the implementation of the ideal. Accordingly, the later the availability of the alternative, the greater the quantity of CFCs that are attributed to that alternative.

Modeling reflects the market penetration potential for each substitute. This means that health effects are dependent on potential market size, so that a low ozone-depleting substitute with large market potential could look worse than a high ozone-depleting substitute with only small uses.

- The quantity of a chemical substitute needed to replace a ODS may not equal the ODS quantity. If replacement is not one-to-one, then the effects of the substitution will not correspond to the ratio of ODPs between the two compounds.

4.6 Global Warming

There is no doubt that human activity is increasing the concentration of greenhouse gases in the atmosphere. The sources and industrial sectors contributing these gases are extremely varied. No single economic sector can be held entirely responsible for the greenhouse effect, nor can a single source, because it contributes only a small amount to the problem, be exempt from accountability. Additional research is needed to better characterize the effects of greenhouse gas emissions on the environment and to evaluate the benefit of various reduction strategies. However, as in the case of ozone depletion, there is growing international consensus among scientists and policymakers that immediate efforts are necessary to curb the rate of growth of atmospheric concentrations of these gases.

Based on total emissions, the major greenhouse gases are carbon dioxide (CO₂) and methane (CH₄), and it is on these major contributors that EPA has focused much of the effort of its nascent voluntary programs such as Green Lights. However, a substantial contribution is made in the aggregate by other gases including CFCs, halons, and other halocarbons. These minor or trace gases are important for two reasons. First, although these gases are currently emitted in smaller quantities than CO₂ and CH₄, their effectiveness in influencing climate tends to be greater. Second, while individual use of these gases may add little to the overall burden, the rising concentration of greenhouse gases in the atmosphere cannot be controlled without addressing the aggregate effect of the trace gases.

As the transition away from the ozone-depleting compounds proceeds, a key policy goal of the SNAP program in reducing overall risk is to be sure that this shift does not also result in a significant rise in contributions to global warming due to an increased reliance on greenhouse gas substitutes. Alternatives reviewed under SNAP to date have varying potential to contribute to global warming. Their contribution depends on many factors evaluated under SNAP, including radiative properties and persistence in the atmosphere. It is difficult to make relative judgements

* Measured against a ceiling that assumes 50 percent of current HCFC-22 use continues.

* Measured against a ceiling that assumes 50 percent of current CFC-11 use continues.

* Measured against a ceiling that assumes 50 percent of current CFC-113 use continues.

among those which do contribute to global warming, however, because their contributions, when viewed through the SNAP lens of individual end-uses, are uniformly small.

Recognizing this, SNAP avoids evaluating the viability of greenhouse gases as substitutes based solely on a single measure, such as an end-use by end-use contribution to actual warming. Instead, a broader evaluation of a substitute's inherent characteristics, such as its absorption spectra and atmospheric lifetime, is used to help clarify whether a substitute could contribute significantly to the problem relative to other substitutes available. For example, a compound which might be acceptable in its contribution to global warming in limited uses might become a problem in widespread emissive uses. Thus, a careful review of the volume likely to be used in a particular end-use, and how much is likely to be emitted from that end-use, also helps. Finally, because SNAP's primary goal is to facilitate the transition away from the ozone-depleting chemicals, a substitute which is also a significant global warming gas might be allowed with controls if there exist few other alternatives in a particular end-use.

This section reviews the risk screen for global warming under SNAP. It includes a discussion of the nature of the global warming problem as well as general properties of greenhouse gases.

4.6.1 The Nature of the Global Warming Problem

The Earth's stable average temperature is maintained by a radiative balance in which the amount of energy absorbed from the sun is equal to the amount of energy radiated back into space by the Earth and atmosphere. If a factor is introduced into the atmosphere that changes this balance, the climate must warm or cool until the radiative fluxes are equal and the balance is restored. A change of this kind is known as a change in radiative forcing (or warming commitment). Radiative forcing, expressed in watts per square meter (W/m^2), is a measure of the downward radiation flux received by the climate system. Concerns about global warming stem from observed increases in the concentrations of certain gases that may be able to alter the climate by causing an increase in radiative forcing.

A characteristic that these gases share is that they absorb radiation in the infrared (or thermal) part of the electromagnetic spectrum. Most of the energy that the Earth receives from the sun is in the form of shortwave radiation in the visible and ultraviolet parts of the spectrum. The energy emitted from the Earth to space is in the form of longwave radiation in the infrared part of the spectrum. These gases absorb some of the outgoing infrared (or thermal) radiation and re-emit it both up into space and back down to the Earth. The net result is a decrease in the heat radiation escaping to space and an increase in the heat radiation falling to the Earth (an increase in radiative forcing). Because this process tends to concentrate heat in the troposphere, it is known as the greenhouse effect. The gases responsible for the greenhouse effect are known as greenhouse gases. Greenhouse gases include carbon dioxide, methane, and nitrous oxide, as well as chlorofluorocarbons (CFCs) and some CFC substitutes.

The greenhouse effect is a natural phenomenon which plays an important role in keeping the Earth warm. Concerns about the greenhouse effect and global warming arise from indications that human activities have been increasing the concentrations of both naturally occurring and anthropogenic greenhouse gases. Increasing concentrations of these gases may lead to an enhanced greenhouse effect, which may cause the Earth to warm at a rate much faster than natural rates of climate change. This accelerated climate change may have a number of adverse consequences including damage to ecosystems, changes in climatic zones, changes in weather patterns, and sea level rise. Adjusting to these changes quickly may be both difficult and expensive.

4.6.2 Properties of Greenhouse Gases

All organic compounds that can volatilize into the atmosphere share the property that they absorb energy in the infrared portion of the electromagnetic spectrum. However, these gases do not all absorb infrared radiation equally well, and thus some have greater impacts than others on global warming. The following factors determine the global warming impact of emissions of a particular gas:

- Atmospheric lifetime. Various physical and chemical processes tend to remove and break down chemicals in the atmosphere. Atmospheric lifetime is a measure of how long a gas stays in the atmosphere before it is removed by these processes.¹ The lifetimes of the greenhouse gases are determined by their sources and sinks in the oceans, atmosphere, and biosphere. In general, the most effective greenhouse gases are those with long lifetimes since the impact of long-lived gases is more persistent than the impact of short-lived gases. In some cases this persistence may be cause for concern. With very-long-lived gases it may take thousands of years for concentrations to decline significantly after emissions have stopped. Thus, the impacts these emissions have are essentially irreversible.
- Molecular weight. Emissions are typically measured according to their mass (in kilograms). However, the increase in atmospheric concentration (by volume) resulting from an emission is proportional to the number of molecules in the emission, not the total mass of the emission. The number of molecules in an emission of a given mass is inversely proportional to the molecular weight of the gas emitted. As a result, the molecular weight is needed to determine the increase in concentration resulting from an emission of a given mass. The lower the molecular weight of the gas, the greater the increase in concentration resulting from a given emission.
- Radiative forcing per molecule. This is a measure of the effectiveness of the gas at absorbing infrared radiation emitted by the Earth. It is proportional to the increase in radiative forcing resulting from a given increase in concentration.

Of these factors, only molecular weight is an irreducible characteristic of a gas. Atmospheric lifetime depends on other characteristics such as solubility in water, rates of reaction with other components of the atmosphere, and susceptibility to photolysis. Radiative forcing per molecule depends on a number of characteristics that are relevant to greenhouse gas behavior. These include the following:

- Integrated infrared band strength. Each kind of molecule absorbs energy at a unique set of wavelengths. The wavelengths at which a molecule absorbs energy are in patterns of contiguous regions in the electromagnetic spectrum which are referred to as absorption bands. A

¹ Atmospheric lifetimes are commonly modeled as e-folding lifetimes. This means that the concentration of a gas is assumed to decay exponentially. Concentration through time is given by the following equation:

$$C_t = C_0 e^{-\frac{t}{L}}$$

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where C_t is the concentration at time t , C_0 is the initial concentration, and L is the atmospheric life of the gas. If the initial concentration of a gas is 1 ppb, its concentration after one lifetime is $1/e$ (about 0.37) ppb. After two lifetimes the concentration is $1/e^2$ (about 0.14) ppb. In theory this means that the concentration is never truly zero. However, after a few lifetimes it does become vanishingly small.

molecule's absorption bands together make up its absorption spectrum. The strength of the gas's infrared absorption spectrum is a measure of how well molecules of the gas absorb radiation at their characteristic wavelengths (i.e., the stronger the absorption band, the more energy that is absorbed by the molecule).

- Location of infrared absorption bands. The location of the gas's infrared absorption bands is important for two reasons: First, the energy radiated from the earth is not evenly distributed across the infrared spectrum. More energy is radiated at some wavelengths than at others. Molecules with absorption bands at wavelengths of high infrared radiation will tend to be more effective greenhouse gases than molecules with absorption bands at wavelengths of low infrared radiation. Second, the impact of a greenhouse gas may be reduced if its absorption bands overlap with those of other gases present in the atmosphere in significant quantities. For example, if a gas has absorption bands that overlap with those of an abundant greenhouse gas like carbon dioxide, the relative impact of the gas on radiative forcing is reduced since much of the energy at these wavelengths is already absorbed.
- Initial concentration of the gas. If the initial atmospheric concentration of a gas is high enough so that a significant portion of the energy at relevant wavelengths is already absorbed, the impact of additional increases in concentration is reduced. This effect is significant for carbon dioxide. It is not significant for CFCs and CFC substitutes since they are present in much smaller quantities than carbon dioxide. Radiative forcing scales linearly with concentration for these chemicals.

A useful index for comparing emissions that incorporates all of these factors is the Global Warming Potential (GWP). The GWP depends on the position and strength of the absorption bands of the gas, its lifetime in the atmosphere, its molecular weight, and the time period over which the climate effects are of concern. Specifically, the GWP is defined as the time-integrated change in radiative forcing resulting from a kilogram of emissions of a given chemical relative to the time-integrated change in radiative forcing resulting from a kilogram of emissions of a reference gas, typically carbon dioxide.²

Because different gases have different lifetimes, the period of integration has an important impact on relative GWPs. This point is illustrated by the example of two different gases, each with an initial concentration of 1 ppb. If the lifetime of the first gas is 10 years, its concentration will be $1/e^{10}$ (0.00005) ppb after 100 years (ten lifetimes). A 100-year GWP captures the entire impact of this gas since the concentration of the gas is effectively zero at the end of the period of integration, and it can no longer influence radiative forcing. If the lifetime of the second gas is 100 years, its concentration will be $1/e$ (about 0.37) ppb after 100 years (one lifetime). A 100-year GWP does not capture the entire impact of this gas since the gas is still present in significant quantities at the end of the period of integration, and it still affects radiative forcing. If the period of integration were lengthened, the ratio of GWPs between the long-lived and the short-lived gases would increase because the value of the integral in the numerator would increase, while the value of the integral in the denominator would remain the same.

² Climate Change: The IPCC Scientific Assessment. Intergovernmental Panel on Climate Change. 1990.

4.6.3 Properties of ODSs and ODS Substitutes

Exhibit 4-8 presents atmospheric lifetime, molecular weight, integrated infrared band strength and GWPs for a number of CFCs, halons, and their substitutes. Although there is overlap between categories, in general the PFCs have the highest GWPs among ODS substitutes. HFCs are next, followed by HCFCs, which have the lowest GWPs. PFCs have high GWPs because of their high integrated band strengths and their extremely long atmospheric lifetimes. HCFCs generally have low GWPs because of their short atmospheric lifetimes (see Exhibit 4-8). HFCs typically fall in the middle because of strong integrated band strengths and moderate atmospheric lifetimes. In examining this table the following issues should be considered:

- Although the GWPs of ODSs and ODS substitutes may be thousands of times the GWP of the reference gas, carbon dioxide, this is offset by the fact that emissions of these compounds are orders of magnitude smaller than emissions of carbon dioxide. Nevertheless, it is estimated that CFCs accounted for about 23 percent of the direct radiative forcing from US emissions of greenhouse gases in 1990.³
- If the lifetime of a chemical is short compared to the lifetime of the reference gas, the GWP of the chemical declines as the period of integration increases. If the lifetime of the chemical is long compared to the lifetime of the reference gas, the GWP of the chemical rises as the period of integration increases.⁴
- In practice a high GWP does not necessarily mean a large impact on warming. If chemicals are never emitted they cannot cause a direct contribution to global warming even if they have high GWPs. For example, if good service practices are in place, emissions from hermetically sealed household refrigerators are very small. If the material is recovered for recycling or destruction after the useful life of the equipment, the refrigerant is never released to affect the atmosphere. In contrast, mobile air conditioners tend to be leaky. Substitutes used in this end use are more likely to be released to the atmosphere and, thus, impact global warming.

³ This estimate does not account for the indirect atmospheric effect of CFC emissions on radiative forcing. CFCs play a role in the depletion of stratospheric ozone, which is itself a radiatively active gas. Ozone depletion may reduce the net increase in radiative forcing that would otherwise occur as a result of CFC emissions. This indirect effect does not apply to HFC and PFC emissions, which are not ozone depleting.

⁴ Because carbon dioxide is removed from the atmosphere through complex processes that cannot be modeled as simple exponential decay, this relationship is not always monotonic.

CHAPTER 4 REFERENCES

EPA. 1992. *Regulatory Impact Analysis: Compliance with Section 604 of the Clean Air Act for the Phaseout of Ozone Depleting Substances*, Appendix A. Washington, D.C. March 12, 1992.

U.S. EPA. 1987. *Assessing the Risks of Trace Gases that Can Modify the Stratosphere*. Office of Air and Radiation. December, 1987.

Isaksen, I.S.A. 1986. *Ozone Perturbation Studies in a Two Dimensional Model with Temperature Feedbacks in the Stratosphere Included*. Presented at the UNEP Workshop on the Control of Chlorofluorocarbons, Leesburg, Virginia. September 1986.

NASA. 1989. *An Assessment Model for Atmospheric Composition*. National Aeronautics and Space Administration Conference Publication 3023.